Biomechanics of Spinal Fracture

For more information contact **John H. Kinney**
(925) 422-6669, kinney3@llnl.gov

Spinal fractures are the most common injuries associated with osteoporosis. The vertebra is composed of a latticework structure known as trabecular bone. We believe that most, if not all, of the tenfold decrease in the sustainable load of osteoporotic vertebrae can be explained by the age-related deterioration of trabecular architecture (see Figs. 1 and 2). In a departure from current thinking, we hypothesized that vertebral failure in older adults is initiated by loss of stability, or buckling.

Project Goals

Our goal was to test this hypothesis using advanced imaging and computational methods. Vertebrae from the skeletal archives of the Smithsonian Institution were imaged on the UC-Beamline at the Advanced Light Source, and geometric nonlinear finite-element analyses were used to simulate load displacement behavior from these "as-built" models. A positive test of the hypothesis will influence how osteoporosis is diagnosed and treated.

Relevance to LLNL Mission

The simulation effort is relevant to advanced simulation and computing in support of stockpile assessment, in which the ability to perform as-built, multiscale modeling is of the highest importance. The imaging tasks add further capabilities for NIF target characterization. Also, the application to nonlinear materials modeling of the osteoporotic fracture is relevant to LLNL's mission in bioscience to improve human health.

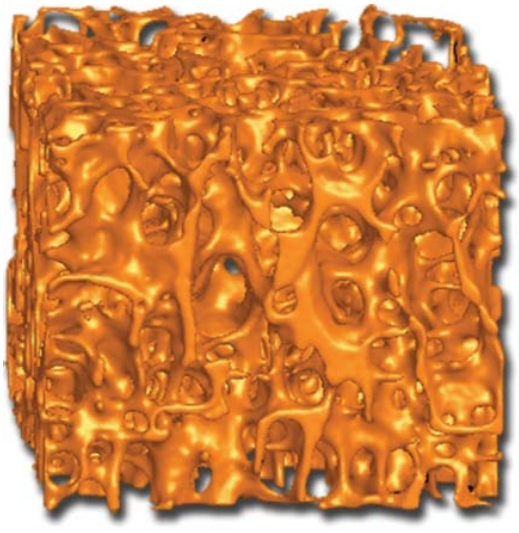

Figure 1. 3-D synchrotron micro-CT image of a 4-mm cube of trabecular bone from the interior of the vertebra of a 30-year-old female. The image shows bone of normal density and architecture: an open-celled foam with a significant number of plates aligned in the load-bearing direction.

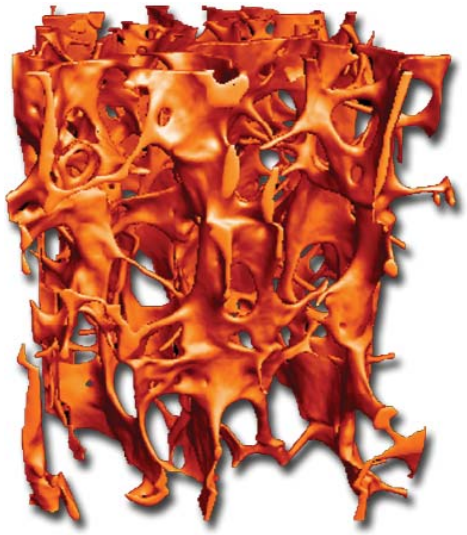

Figure 2. 3-D synchrotron micro-CT image of a 4-mm cube of trabecular bone from the interior of the vertebra of a 63-year-old male. The aged adult presents a markedly different trabecular architecture: fewer plate-like structures and many more high-aspect-ratio rod-like members.

FY2004 Accomplishments and Results

We discovered that there is a transition from strength-initiated failure to stability-initiated failure with age, where failure in osteoporotic vertebrae is mediated by instability of the individual trabecular members. We also uncovered evidence that osteoporotic vertebrae are hypersensitive to small imperfections. The small cavities caused by the cellular process of bone resorption are sufficient to destabilize the trabecular lattice under the right conditions. This provides a physical explanation of the clinical observation that bone remodeling is an independent predictor of fracture risk.

Figure 3 shows our results for tests on a 30-year-old female and a 63-year-old male. The distribution functions are superposed over the Euler hyperbola, as a function of applied stress (normalized to the yield stress of the tissue) and the slenderness ratio. At a slenderness ratio greater than the critical value, λ_c, failure occurs from elastic buckling of the trabecular members. At slenderness ratios less than λ_c, failure is initiated by yielding of the members. There appears to be an age-related increase in the fraction of trabecular members that have slenderness ratios greater than λ_c; the 30-year-old female has only a minor number of such members, while in the 63-year-old male, over 30% of the trabecular members are greater than λ_c.

The trabecular structures in Figs. 1 and 2 were meshed, and the stress-strain response was simulated on a parallel version of NIKE3D. The partitioning between the amount of nonlinear deformation from geometric nonlinear (elastic) response, and the nonlinear deformation from yielding, was examined as a function of the applied stress (normalized to the ultimate strength). In the 30-year-old female, the nonlinear deformation was entirely a result of tissue yielding, whereas, in the 63-year-old male the majority of the nonlinear deformation resulted from buckling of the trabecular members.

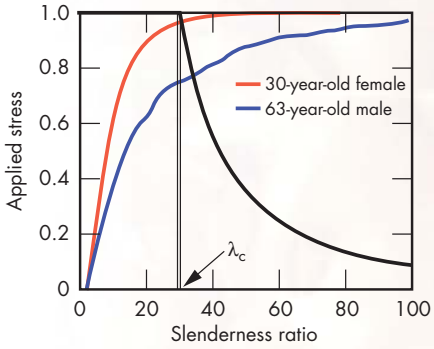

Figure 3. Graph showing the cumulative distribution functions of the slenderness ratios of the trabecular bone in two subjects of different ages. The critical value, λ_c, is indicated.

This complete reversal in the mechanisms of nonlinear deformation suggests that there may be a transition from stable lattice behavior to unstable lattice behavior, as a result of age-related loss of bone.

This work will change the diagnostic focus from simply measuring bone mass to considering factors that influence buckling, such as the aspect ratio of the trabeculae. Not only will risk estimates improve, but also it will be possible to select the optimal treatment strategies for an individual.

Related References

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